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Metal-Insulator Transition in a Low-Mobility Two-Dimensional Electron System

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Abstract

We have varied the disorder in a two-dimensional electron system in silicon by applying substrate bias. When the disorder becomes sufficiently low, we observe the emergence of the metallic phase, and find evidence for a metal-insulator transition (MIT): the single-parameter scaling of conductivity with temperature near a critical electron density. We obtain the scaling function β, which determines the length (or temperature) dependence of the conductance. β is smooth and monotonic, and linear in the logarithm of the conductance near the MIT, in agreement with the scaling theory for interacting systems.

Keywords: metal-insulator transition, strong correlations, two-dimensional system

1. Introduction

Recent experiments [1,2] on a two-dimensional electron system (2DES) in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) have provided solid evidence for the existence of a metal-insulator transition (MIT) at zero magnetic field in this 2D structure, raising speculation that this transition is driven by electron-electron interactions. However, the disorder in Si MOSFETs at the transition is also strong, as indicated by the reported [1,2] values of the critical conductivity $\sigma_c \sim e^2/2h$ (corresponding to $k_F l \lesssim 1$, where k_F–Fermi wavevector, l–mean free path). Experiments on mesoscopic Si MOSFETs [3] and a recent observation of a MIT in clean ($k_F l \approx 40$) Si/SiGe devices [4] with a similar value of the critical electron density n_c, support strongly the view that electron-electron interaction is the most relevant energy scale at the MIT. In this paper, however, we focus on the role of disorder, and show that the metallic phase emerges only when the disorder is sufficiently low. We also discuss the form of the conductance scaling function ("beta function" [5]), which defines the (length, temperature) scale dependence of the conductance. Our results seem to be consistent with the suggestion [6] that the 2D metal is not a Fermi liquid.

2. Experiment

We present results obtained on n-channel MOSFETs fabricated on the (100) surface of Si doped at $\approx 8.3 \times 10^{14}$ acceptors/cm^3 with 435 Å gate oxide thickness and oxide charge $\approx 3 \times 10^{10}$cm^{-2}. The samples had a Corbino (circular) geometry with the channel length $L = 0.4$ mm and width $W = 8$ mm. Conductance G was measured as a function of gate voltage V_g (proportional to carrier density n_s) at temperatures $1.2 < T < 4.2$ K, using a lock-in at a frequency of ~ 100 Hz and an excitation voltage of 0.3 mV. The peak mobility, which is a rough measure of the amount of disorder [7], was 0.5–0.8 m^2/Vs at

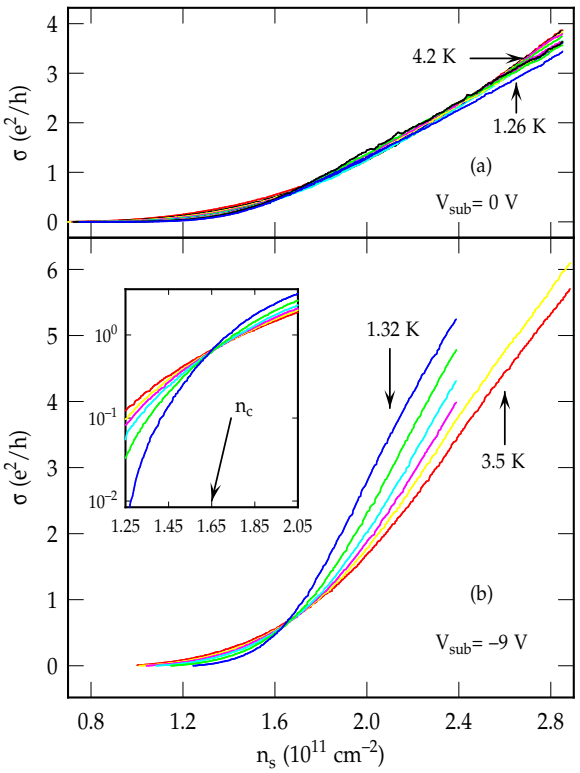

FIG. 1. Conductivity σ of sample #1 as a function of n_s for (a) T =4.2, 3.6, 3.2, 2.8, 2.5, 2.3, 2.09, 1.93, 1.79, 1.67, 1.57, 1.21 K and $V_{sub} = 0$ V, and (b) T =3.5, 3.0, 2.7, 2.3, 1.85, 1.32 K and $V_{sub} = -9$ V. In (a), σ decreases for all n_s as T is lowered. In (b), σ increases as T goes down for all $n_s > n_c$. The inset shows the same data around n_c with σ on a logarithmic scale.

4.2 K. In these samples, all electronic states are localized, in agreement with early studies [8]. Fig. 1(a) shows the conductivity $\sigma = GL/W$ for one of the samples (sample #1), as a function of electron density n_s for several temperatures. As T is lowered, σ decreases for both low and high n_s, indicating insulating behavior. The temperature dependence is weaker at intermediate values of n_s, which is probably a precursor of the critical behavior discussed below.

By applying the reverse substrate bias we have been able to decrease the disorder scattering and increase the mobility at all carrier densities [9], with the peak mobility going up to $\approx$1 m^2/Vs at 4.2 K. At that point, the mobility becomes sufficiently high at carrier densities low enough to allow the Coulomb interaction energy U to be much greater than the Fermi energy E_F [1,6] (in our samples, $U \approx 150$ K $\gg E_F \approx 12$ K), and we observe the metal-insulator transition, as shown in Fig. 1(b) for $V_{sub} = -9$ V: the temperature dependent behavior of σ is now reversed for all n_s above $n_c = (1.65 \pm 0.02) \times 10^{11}$cm^{-2}, as expected for metallic behavior. For $n_s < n_c$, the 2DES exhibits insulating behavior as before.

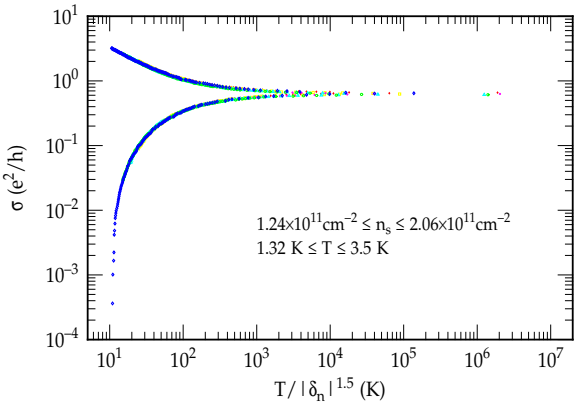

FIG. 2. Scaling of conductivity with temperature for sample #1, using the data shown in Fig. 1(b) in the n_s and T ranges given on the plot.

3. Scaling analysis

Fig. 2 shows the scaling of σ with temperature near the transition according to

$$\sigma(T, n_s) = f(|\delta_n|/T^{1/z\nu}) = \sigma(T/T_0), \qquad (1)$$

with a single parameter T_0 that is the same function of $\delta_n \equiv (n_s - n_c)/n_c$ on both the metallic and the insulating side of the transition, $T_0 \propto |\delta_n|^{z\nu}$. Here z is the dynamical exponent, and ν is the correlation length exponent. The best collapse is found for $z\nu = 1.5 \pm 0.1$, in excellent agreement with other studies on Si MOSFETs [1].

A quantity of special interest is the scaling function [5] $\beta(g) = d[\log(g)]/d[\log(L)]$ (where $g = \sigma/(e^2/h)$ is a dimensionless conductance), which describes the length scale dependence of the conductance. At non-zero temperatures, the effective sample size is $L_{eff} \sim T^{-1/z}$ [6,10–12], so that $\beta(g)$ determines the temperature dependence of the conductance. In particular, the shape of β at large g determines the temperature dependence of the metallic phase. For non-interacting systems and for Fermi liquid systems, $\beta(g) = (d-2)$ for $g \to +\infty$ (d–dimension), which is equivalent to Ohm's law. However, it has been argued [6] that the 2D metallic phase is *not* a Fermi liquid but some more exotic state. In general, one does not expect Ohm's law to hold for non-Fermi liquid metals, as is well known, for example, in the case of a Luttinger liquid [13]. Instead, conductance could display a non-trivial length

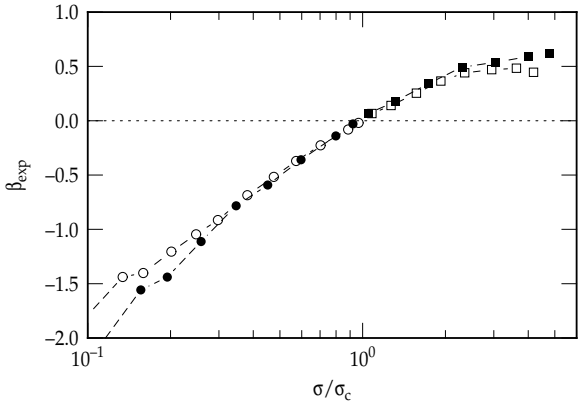

FIG. 3. $\beta(g)$ vs. conductance on a logarithmic scale. β_{exp} was derived from the data such as those shown in Fig. 2: dots were obtained from the insulating branch, and squares from the metallic branch. Solid symbols: sample #1, $\sigma_c = 0.65\ e^2/h$; open symbols: sample #5, $\sigma_c = 0.5\ e^2/h$.

dependence even in the limit $g \to +\infty$. Therefore, it is interesting to examine experimentally the behavior of $\beta(g)$, in order to obtain clues about the nature of the metallic phase in 2D. More specifically, if experiments suggest that $\beta \neq 0$ as $g \to +\infty$, such behavior would be consistent with a non-Fermi liquid metallic state.

Fig. 3 shows an analogous scaling function $\beta_{exp} = -d[\log g]/d[\log T]$ for two of our samples. $\beta_{exp}(g)$ changes sign for $\sigma = \sigma_c$, as expected at the metal-insulator transition. The shape of β_{exp} near the transition is consistent with the suggestion [6] that, on a logarithmic scale, $\beta(g)$ is linear over an appreciable range of conductances. β_{exp} increases monotonically and, most interestingly, may saturate at a value of 0.5 for large g. If this behavior would persist for arbitrary large values of g, it would indicate that the metallic phase is a non-Fermi liquid, characterized by conductance diverging as $T^{-1/2}$ when $T \to 0$. Another possibility is that there is a broad maximum in $\beta(g)$ and that it will turn back down toward the value of zero in accordance with Ohm's law. In either case, however, we have a clear violation of the scaling picture for non-interacting systems [5], where $\beta < 0$ for $d = 2$.

The data obtained on high-mobility Si MOSFETs [14] yielded $\beta(g)$ with only a monotonic increase with $\log g$, up to a value of about 1, in exactly the same range of g as our data (Fig. 3). At higher values of g, $\beta(g)$ turned back down toward zero, with no indication of a saturation. In that range of g, however, the scaling failed and $\beta(g)$ could not be extracted reliably from the data [14,15]. Clearly, it would be interesting to study the beta function at much higher values of g, for which systems other than Si MOSFETs might be more appropriate [4].

4. Conclusion

In summary, we have shown how the metallic phase can be created by reducing the disorder scattering on a single sample. The resulting scaling behavior of conductivity with temperature provides convincing evidence for the existence of a metal-insulator transition in this 2D system. In addition, the results of our scaling analysis seem to be consistent with the suggestion that the 2D metal is not a Fermi liquid.

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